

# Evaluation of 2D models for the prediction of surface depression storage using realistic reference values

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## Abstract:

Depression storage (DS) is the maximum storage of precipitation and runoff in the soil surface at a given slope. The DS is determined by soil roughness that in agricultural soils is largely affected by tillage. The direct measurement of DS is not straightforward because of the natural permeability of the soil. Therefore, DS has generally been estimated from 2D/3D empirical relationships and numerical algorithms based on roughness indexes and height measurements of the soil surface, respectively. The objective of this work was to evaluate the performance of some 2D models for DS, using direct and reliable measurements of DS in an agricultural soil as reference values. The study was carried out in experimental microplots where DS was measured in six situations resulting from the combination of three types of tillage carried out parallel and perpendicular to the main slope. Those data were used as reference to evaluate four empirical models and a numerical method. Longitudinal altitudinal profiles of the relief were obtained by a laser profilometer. Infiltration measurements were carried out before and after tillage. The DS was largely affected by tillage and its direction. Highest values of DS are found on rougher surfaces mainly when macroforms cut off the dominant slope. The empirical models had a limited performance while the numerical method was the most effective, even so, with an important variability. In addition, a correct hydrological management should take into account that each type of soil tillage affects infiltration rate differently. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS depression storage; roughness index; modelling; agricultural soil; tillage

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## INTRODUCTION

Surface depression storage (DS) of water in the soil is understood as being the maximum amount of water that can be retained on the soil's surface on a certain slope. In undisturbed soils with no vegetation, DS is determined by the actual roughness of the soil, which is mostly because of the characteristics of its aggregates. However, in tilled soils, this roughness would mainly be generated by the alteration in the relief caused by different tillage implements (Romkens and Wang, 1986; McKinney *et al.*, 2012). In fact, DS could also be affected by tillage direction – with respect to the main slope – (Álvarez-Mozos *et al.*, 2011) because this, in turn, influences runoff (Takken *et al.*, 2001).

It is thus that the volume of water resulting from the excess of rain over infiltration is partially and temporally retained in the small depressions in the soil surface. The water – then immobilized – would have more time to infiltrate, therefore reducing the risk of erosion from

runoff (McKinney *et al.*, 2012), so that the water storage in the soil profile would be favoured. Furthermore, this water storage can be a determinant in the response of the water table to rain events and in the duration and magnitude of the surface flows (Gayle and Skaggs, 1978). The DS is precisely taken into account in diverse erosion models such as LISEM (De Roo *et al.*, 1996), EUROSEM (Morgan *et al.*, 1998), AnnAGNPS (Bingner *et al.*, 2012), WEPP (Flanagan *et al.*, 2007) and MIKE SHE (Refsgaard and Storm, 1995).

Being soil highly permeable and the estimation of hydraulic conductivity very variable and therefore difficult to determine (Langhans *et al.*, 2011), the direct measurement of DS by discharging water on its surface would not be possible without any previous impermeabilization treatment that did not alter its natural roughness. Impermeabilization can be obtained by the impregnation of the soil with a resin or plastic film (Gayle and Skaggs, 1978; Takken and Govers, 2000). Another alternative is to resort to the reproduction of the soil surface using some impermeable material (Foster *et al.*, 1984; Kamphorst and Duval, 2001; Roche *et al.*, 2007; Antoine *et al.*, 2012). However, any of these techniques

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is, to a greater or lesser extent, difficult, laborious and costly, and therefore, they are little used (McKinney *et al.*, 2012).

Hence, the DS value in the different hydrological models is estimated – assuming a certain error – on the basis of empirical relationships between that storage and roughness indexes. Among the latter, those most used are random roughness (RR) (Allmaras *et al.*, 1966), limit difference (LD), limit slope (LS) (Linden *et al.*, 1988), tortuosity (T) (Boiffin, 1984) and mean upslope depression (MUD) index (Hansen *et al.*, 1999). It is noteworthy that in most of those models, tillage direction is neglected. Also, numerical algorithms are frequently used. Thus, from height measurements of the soil surface, generally by means of profilometers, digital elevation models (DEM) are created in two or three dimensions. Then, the DEM is ‘virtually’ filled with water using an *ad hoc* algorithm (e.g. Planchon and Darvoux, 1999; Álvarez-Mozos *et al.*, 2011). Basically, the depressions are recursively located, and their volume/area is calculated up to their pour point. It should be mentioned that the 2D models, as they are more easily obtained than 3D ones, are, ultimately, those most used despite their evident simplicity.

However, few works have made an exhaustive evaluation of models estimating surface DS (e.g. Kamphorst *et al.*, 2000), and even fewer, as can be understood for all the previous reasons, by using *real* DS – i.e. direct measurements of DS – as reference values (Antoine *et al.*, 2012).

The main objective of this work was to evaluate the performance of some of the best-known 2D predictive models of surface DS, from *in situ* and reliable measurements of DS of an agricultural soil, subjected to three different types of tillage.

The study was carried out in the field, in experimental microplots (of approximately 1 m<sup>2</sup>). The DS was measured in a sloping soil subjected to three types of tillage in two opposite tillage directions (parallel and perpendicular to the main slope of the plot). Then, those data were used as reference to evaluate four known empirical models and a numerical method conceived for the estimation of DS. For this purpose, longitudinal altitudinal profiles of the terrain were obtained by a high precision laser profilometer.

## MATERIAL AND METHODS

### *Experiment site and treatment definition*

The experiment was conducted on a homogeneous hillslope – 600 m<sup>2</sup> – with a dominant slope of 10–15%, located in the experimental field at the Higher Technical School of Agricultural Engineers of the Universidad Pública de Navarra (Navarre, Spain) (Figure 1). The soil

is silty clay loam in texture (sand = 13.8%, silt = 53.9%, clay = 32.3%) with organic matter content = 1.8%.

At five points on this slope, the infiltration rate of the soil profile was measured – with a double ring infiltrometer, Porta *et al.* (2005) – until constant values were reached (i.e. basic infiltration).

Next, within the hillslope, six treatments were defined (Table I), resulting from the combination of three tillage types – mouldboard plough + roller compacted (MR), chisel + harrow (C) and rotavator (R) – carried out in two different directions, parallel (f) and perpendicular (c) to the main slope of the plot.

In each of the six treatments, two more or less square experimental microplots (0.8–1 m<sup>2</sup>) were demarcated (Figure 1). The 12 microplots were treated equally in the way described as follows.

First, the perimeter of the microplot was delimited. For this purpose, three sheets of stainless steel 800–1000 mm long, 120 mm high (20 mm buried) and a few millimetres thick were inserted in the soil. The fourth limit was constituted by a collector gutter in the lowest area of the microplot. The gutter, slightly tilted, ended in a collecting recipient located at its lowest end (Figure 1).

Once the microplot was set up, its impermeabilization began. This was carried out by spraying on the soil four to six layers (one after the former had been absorbed) of wood glue diluted in water in order to harden it and seal its small pores. Once the glue was dry, several layers of impermeabilizing paint were carefully applied manually, with brushes of different thicknesses, always respecting the characteristic roughness of each tillage and taking care not to alter the depressions because of microroughness. Then, once the paint was dry, it was verified, by means of localized applications of water, that the potential leak areas were well impermeabilized.

Also, in each treatment and aided by a laser profilometer (Giménez *et al.*, 2009), five longitudinal height profiles were made, always in the direction of the main slope of the plot. Each of the five profiles was, approximately, 1000 mm long, with readings every 5 mm. The precision of the height data (axis *z*) was of 0.5 mm.

In five microplots (MRf1, MRf2, Rc1, Rc2, Cc1 and Cc2), the longitudinal height profiles were prolonged, by approximately 1000 mm, further on from the area treated (impermeabilized with glue and paint), on soil also tilled but untreated (without glue and paint). These situations were used to investigate possible changes in surface roughness because of disturbance caused by the application of glue and paint layers. It was feared, above all, that certain depressions in the soil surface might have been partly filled up by an excessive amount of paint, thus altering their internal volume and, therefore, their ability to store water. This fact would be reflected when contrasting each pair of longitudinal height profiles

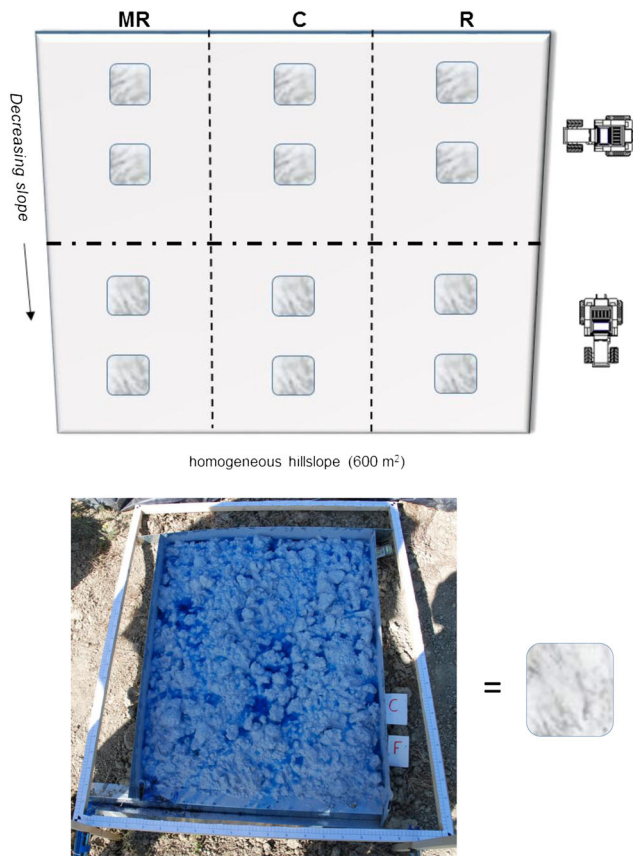


Figure 1. (Up) Sketch of the experimental set-up in the field. Six treatments were defined resulting from the combination of three tillage types – mouldboard plough+roller compacted (MR), chisel+harrow (C) and rotavator (R) – carried out in two different directions, parallel and perpendicular to the main slope of the plot. Two microplots per each treatment were set up. (Down) Microplot showing its waterproof surface and soon after finishing an experiment. Water storage areas are highlighted in blue by the action of methylene blue

Table I. Treatment (type of tillage) description

Treatment <sup>a</sup>	Description
MRf	Tillage operation performed with a mouldboard followed by a compacting roller. Tillage depth was 20–22 cm.
MRc	
Rf	Operation performed with a rotavator at a depth of 10–12 cm.
Rc	
Cf	Operation performed with a chisel, down to 35 cm deep, followed by a harrow.
Cc	

<sup>a</sup> f and c mean tillage performed parallel and perpendicular to the main slope, respectively.

(treated soil vs untreated soil) in each of the five situations selected. For this purpose, from each height profile (corrected per slope), the percentile-98 of the values of  $z$  or heights was obtained, i.e. 2% of the maximum extreme values of  $z$  were excluded. This filtering of extreme values was made with the aim of eliminating any possible outlier values not therefore representative of the microrelief. Next, the difference between this maximum value (percentile-98) and each height value along the profile – axis  $x$  – was obtained, thus achieving a population of normalized data. It should be pointed out that minimum height values were not used as a reference as they would be those that would precisely be more affected by the impermeabilization treatment, because of the potential filling in of the depressed areas, as indicated in the preceding texts. Subsequently, in the five situations, analyses of variance (ANOVA) were made, contrasting the differences in heights between each pair of profiles (treated and untreated soils).

Finally, new infiltration measurements similar to the previous ones were carried out, but this time, two measurements were made in each type of tillage (MR, R and C). It was aimed to see if the infiltration rate varied once the soil was tilled.

#### Experimental protocol

In each of the 12 microplots (six treatments, two replications each), experiments were carried out as follows.

A small amount of methylene blue (a colourant soluble in water) was added to a known volume of water. The methylene blue permitted, on one hand, an analysis of the ‘paths’ through which the water flowed and, on the other, the estimation of the spatial distribution pattern of surface water storage (Figure 1).

The coloured water was gently poured over the microplot with oscillatory movements, first, along the upper edge, then moving gradually down until the whole surface was homogeneously covered. This simulated the natural process of the filling in of the soil depressions because of runoff and rain events; a similar procedure was followed by McKinney *et al.* (2012). The water went on being applied until it was verified that the surface reached its maximum storage capacity. Thus, from the difference between the natural water input and the water collected in the collection recipient, the volume of the water stored in the surface was obtained. Then, the water stored was carefully absorbed (performed with sponges), and the surface dried in the open air. This operation was repeated three to four times until a constancy in the value of the stored water measured was ensured.

At the end of the last replication in the measuring of stored water, and with the help of a limnimeter, the water depth was measured at five or six points, which were



representative of the different storage microdepressions observed. These measurements were taken far away from the edges of the plot to prevent any possible overestimations in the reading.

A levelled graduated frame was put around the microplot, and photographs of the microplot surface were taken (Figure 1). The images were then rectified – taking the graduated frame as a control – and subsequently processed (using geographic information system-specific software) in order to obtain binary images, thus defining the water-covered areas (water storage areas) from the uncovered ones (Figure 1, water storage area in blue).

The whole experiment was recorded in video for future studies on water flow dynamics and connectivity.

Although all the microplots were located on a homogeneous hillslope, they did not all have the same slope (Table II). Although the variation range of the slope was a narrow one (between 10 and 15%), it had to be taken into consideration because it is known that DS is highly sensitive to changes in land inclination (e.g. Onstad, 1984; Linden *et al.*, 1988; Álvarez-Mozos *et al.*, 2011). Therefore, the experimental values of DS (refer in the preceding texts) were recalculated considering a single slope of 10% (Table II). For this purpose, one of the six expressions proposed by Álvarez-Mozos *et al.* (2011) was used. These authors relate the maximum DS to the slope (S) for a certain type of roughness triggered by tillage. To be specific, of all the Álvarez-Mozos' *et al.* formulas, the one (Equation (1)) considered to be nearest to our conditions was chosen. These six formulas are, in any case, very similar to each other in spite of covering a much wider range of roughness than that found in the present work. Likewise, McKinney *et al.* (2012) measured the DS of moulds (0.5 m<sup>2</sup>) obtained from soils of a different roughness – the latter being generated by different tillage implements and by crop residues – and at different slopes (0.25–7%). It was observed that the percentage variation in DS associated with the slope (Table IV in McKinney *et al.*, 2012) was similar to that estimated by Equation (1).

$$MDS = 3.67 + 24.1 e^{(-0.08 S)} \quad (1)$$

Equation (1) was also used to estimate the DS at other slope values: 0, 5, 15, 20, 30 and 40% (Table II). The recalculation of DS at slopes much further away from the experimental value (10%) would be subject to, of course, a larger error, especially in the range of low slopes (<10%), in which the variations in DS per slope unit are important (refer to Equation (1)). Then, by means of Equation (1), the percentage change, which a given value of DS would undergo when going from one slope to a different one (e.g. 13 to 10%), was estimated. Although Equation (1) is of an exponential type, the changes in DS

in the slope range between 10 and 15% (our experimentation values) were relatively small, so that making this adjustment would not have incurred any important errors.

#### Characterization of the microforms/macroforms on the soil surface

Taking the height data obtained with the profilometer (refer in the preceding texts), different roughness parameters commonly used for soil surface description were determined as follows:

1. RR (Allmaras *et al.*, 1966). It is the standard deviation of the height data previously corrected per slope.

$$RR = \frac{1}{n} \sum_{i=1}^n (z_i - z)^2 \quad (2)$$

where

$z_i$  = height at each point.

$z$  = mean of the heights.

$n$  = number of points.

Among the authors who have used this index, there is a certain disagreement with regards to the way height data are dealt with before the calculation of their standard deviation (Chu *et al.*, 2012). These data are sometimes modified either by eliminating 10% of the extreme values – i.e. maximum and minimum height – and/or by applying a logarithm to the original data (e.g. Currence and Lovely, 1970). Then, the standard deviation is calculated on the modified data. In this work, the RR was calculated (i) just from the original data (RR), (ii) after removing extreme values (R10%) and (iii) after applying logarithm to the original data. In this last case, the final value (RRLn) results from multiplying the value of the standard deviation by the mean of the original height data (Chu *et al.*, 2012; McKinney *et al.*, 2012).

2. Limit elevation difference (LD) and slope (LS) (Linden and Van Doren Jr, 1986). These two indexes are based on the calculation of the first-order semivariogram of the height data.

$$\Delta z_h = \sum_{i=1}^n |z_i - z_{(i+n)}| / n \quad (3)$$

where

$Z_i$  = height at each point.

$Z_{i+n}$  = height at a point situated at a distance  $h$  from  $Z_i$ .

$n$  = number of data.

Table II. Average values of depression storage for the different treatments (refer to Table I for descriptions of the treatments)

Treatment	DS (mm)	Slope <sup>a</sup>	DS <sup>b</sup> adjusted	Estimated DS at different slopes					
				0%	5%	15%	20%	30%	40%
MRf	4.43	9.5	4.44	7.72	5.81	3.46	2.79	2.00	1.60
Rf	6.74	10.5	6.74	11.73	8.83	5.26	4.25	3.03	2.43
Cf	3.22	10.1	3.23	5.61	4.22	2.52	2.03	1.45	1.16
MRc	2.02	12.8	2.30	4.01	3.02	1.80	1.45	1.04	0.83
Rc	13.56	15.4	16.54	28.77	21.66	13.56	10.42	7.44	5.95
Cc	8.75	13.7	10.32	17.96	13.52	8.05	6.50	4.64	3.71

<sup>a</sup> Measured within the experimental microplot.<sup>b</sup> DS recalculated at a slope of 10%.

The first-order semivariogram is the graphic of  $\Delta Z_h$  as a function of  $h$ ; it can be approximated by a linear model defined by

$$1/\Delta Z_h = a + b (1/h) \quad (4)$$

where  $a$  and  $b$  are parameters calculated by means of a regression analysis;  $a$  might represent the spatial correlation degree in short distances whereas  $b$  in longer distances. The LD and LS are then defined as

$$LD = 1/a \text{ and } LS = 1/b \quad (5)$$

Therefore, LD supplies information on the microrelief characteristics at long distances. As for LS, it is used to characterize roughness at short distances (Vidal Vázquez and Taboada Castro, 1999). These indexes provide information on the spatial organization of the microrelief; they possess a physical sense and show a good sensitivity to variations in roughness (Vidal Vázquez and Paz, 2003).

3. Tortuosity index ( $T$ ) (Boiffin, 1984). It is defined as

$$T = L_1/L_0 \quad (6)$$

where

$L_1$  = profile length

$L_0$  = horizontal projection length of the profile.

The  $T$  index is different according to the distance separating the measurement points, i.e. it is dependent on the frequency with which the data are read (Kamphorst *et al.*, 2000).

4. Mean upslope depression (Hansen *et al.*, 1999). It is defined as

$$MUD = \sum_{i=1}^m \left[ \sum_{j=1}^n \Delta z_j / n \right] / m \quad (7)$$

where  $\Delta Z = Z_0 - Z_i$  for  $Z_i < Z_0$ ;  $\Delta Z = 0$  for  $Z_i \geq Z_0$

$Z_i$  = height reading on subsegment.

$Z_0$  = reference point on subsegment.

$m$  = number of subsegments per transect.

$n$  = number of height readings per subsegment.

5. Index  $R$  (Romkens and Wang, 1986). It is defined as

$$R = A \times F \quad (8)$$

where

$A$  = microrelief index, is the area – per unit length – between the measured surface profile and the regression line of least squares through all measured heights on a transect.

$F$  = peak frequency number of height maxima per unit transect length.

In our case,  $F$  was defined from those points describing the larger variation in height and then after neglecting microroughness. In order to discriminate macroforms – especially those induced by tillage – from the natural microroughness of the soil surface, the height profiles were smoothed. Different data smoothing techniques were tried out – e.g. moving average, wavelets – but without obtaining any satisfactory results, because the macroforms were more or less distorted. Finally, the algorithm of Douglas and Peucker (1973) implemented in Matlab permitted the expected smoothing of the altitudinal profiles to be

made (Giménez and Govers, 2001). The parameter  $F$  (Equation ((8))) was determined from the longitudinal profiles transformed in that way.

6. Fractal dimension  $D$  and crossover length  $l$ , based on the fractal theory (Chi *et al.*, 2012). The former describes horizontal roughness – along the longitudinal profile – whereas the latter quantifies the vertical variation in the height data.

#### Empirical models of DS estimation

The four first roughness indexes mentioned in the preceding texts were also used as an explanatory variable of empirical models of DS estimation widely used (Table III), while the longitudinal height profiles – five replications for each treatment – served, likewise, to evaluate the numerical method of DS determination proposed by Álvarez-Mozos *et al.* (2011). Briefly, this numerical method works as explained next. For each horizontal (i.e. corrected for the slope) profile, the DS is calculated using a depression filling algorithm. The algorithm recursively searches for lower points in the profile and determines the area needed to fill all the depressions up to their pour point. This area per unit length is the maximum amount of water storage in millimetres (Álvarez-Mozos *et al.*, 2011).

Model performance assessment was carried out qualitatively through visual inspection of the graphical representations of the relationship between model estimates and observation and quantitatively calculating the root mean square error (RMSE) of each model estimates. Moreover, by bootstrapping resampling method, confidence intervals for RMSE were defined using the Fiteval program (Ritter and Muñoz-Carpena, 2013). Conventional interpretation of the goodness-of-fit measures may be inadequate as they are easily influenced by the small number of data points, outliers and model bias. To avoid or minimized this, Fiteval presents probability distributions of goodness-of-fit measures derived by bootstrapping.

## RESULTS AND DISCUSSION

### Evaluation of the impermeabilization technique employed

The analysis of variance of the different pairs of height profiles (treated soil vs untreated soil) gave significant differences ( $p < 0.01$ ). However, they did not show any defined bias as it could have been, for instance, with smaller differences in height in the treated profiles because of the possible filling up of depressions with paint. It should be understood, therefore, that those differences are typical of the spatial variability of roughness, because the profiles compared, although near to each other, do not coincide in space. Furthermore, on the surface treated with paint, some little details can clearly be observed (Figure 1) like, for example, plant remains of the order of tenths of millimetres thick. This confirmed the scant disturbance caused in the natural microrelief. Therefore, we assumed that the glue/paint application would not have importantly altered the microroughness of the soil.

### Evaluation of the surface roughness

The analysis of roughness – quantified by the different indexes proposed – did not show a single trend among the six types of tillage (Table IV). That is to say, the treatments could be grouped according to their degree of roughness in different ways depending on the roughness parameter considered. In other words, if the different roughness indexes are used to rank the six treatments in increasing or decreasing order of roughness or coarseness, each index classifies the treatments, differently (Table IV).

However, the classification per roughness of treatments defined by the index  $R$  agreed with that expected, namely with that resulting from visual inspections made during the experiments (Table IV, Figure 2). That is, the tillage made perpendicular to the slope (c) showed a greater roughness than that done parallel to it (f). Moreover, in both groups (f and c), the degree of roughness increased in the following order: mouldboard plough + roller compacted (MR), rotavator (R) and chisel + harrow (C). It should be remembered that the altitudinal profiles were

Table III. Empirical models to estimate water depression storage evaluated in this work

Model	Description	Reference
$M_{RR}$	$0.112RR + 0.031RR^2 - 0.012RR \cdot S$	Onstad (1984)
$M_T$	$\text{Exp}[-6.66 + 0.27(T)]$	Morgan <i>et al.</i> (1998)
$M_{LS-LD}$	$0.382\sqrt{LD \cdot LS} + 0.017(\sqrt{LD \cdot LS})S - 0.077$	Linden <i>et al.</i> (1988)
$M_{MUD}$	$0.480 \text{ MUD}$	Hansen <i>et al.</i> (1999)

Random roughness RR was also calculated as R10% and RLn (refer to text).

RR, random roughness; T, tortuosity; LD, limit elevation difference; LS, limit elevation slope; MUD, mean upslope depression; S, slope.

Table IV. Average values of the roughness indexes for the different treatments

	MRf	Rf	Cf	MRc	Rc	Cc
RRsd	10.4 (4.9)	11.3 (2.7)	12.5 (2.4)	6.7 (1.9)	12.2 (3.1)	15.9 (5.0)
RRLn	10.5 (5.1)	10.4 (4.7)	12.4 (2.4)	6.7 (2.0)	12.3 (3.1)	15.7 (4.9)
RR10%	5.6 (2.2)	7.1 (2.8)	8.4 (1.8)	4.9 (1.6)	8.5 (2.8)	10.5 (4.6)
T	16.9 (8.5)	22.0 (5.7)	29.6 (3.3)	14.8 (5.5)	16.0 (6.9)	25.0 (3.2)
MUD	2.0 (1.85)	1.5 (0.5)	2.3 (0.9)	0.7 (0.6)	0.9 (0.7)	2.9 (3.0)
LS	0.6 (0.2)	0.9 (0.3)	1.1 (0.3)	0.7 (0.2)	0.5 (0.1)	0.8 (0.2)
LD	11.3 (5.1)	12.6 (3.6)	14.3 (4.1)	7.7 (2.6)	14.0 (2.6)	19.4 (7.4)
R	150.4 (87.9)	353.9 (120.8)	519.3 (141.0)	233.6 (121.0)	347.0 (187.7)	599.8 (200.6)
D	1.47 (0.054)	1.50 (0.026)	1.53 (0.06)	1.49 (0.05)	1.47 (0.06)	1.50 (0.07)
l	2.68 (2.55)	2.82 (1.18)	4.38 (0.96)	1.49 (0.60)	1.67 (0.89)	3.69 (1.02)

Standard deviation in brackets.

RRsd/Ln/10%, random roughness (refer to Characterization of the microforms/macroforms on the soil surface section for details); T, tortuosity; LD, limit elevation difference; LS, limit elevation slope; MUD, mean upslope depression; D, fractal dimension; l, crossover length. Refer also to Table I.

always tilled following the direction of the dominant slope.

It is worth noting that the LS index correctly classified the degree of roughness but only of the three treatments parallel to the slope (f), whereas the LD index did the same only clearly with those treatments perpendicular to the slope (c) (Table IV). This agrees with the fact that LS gives information on the relief characteristics at short distances, while LD provides it for long ones (Linden and Van Doren Jr, 1986; Vidal Vázquez and Taboada Castro, 1999). The macroforms associated with tillage appeared precisely in the long distances (tens of centimetres), while the microroughness, because of soil clods and aggregates, did so, instead, at shorter distances.

#### Measurements of surface storage in the different treatments

As expected, marked differences in DS according to the type and direction of the tillage were observed (Table II).

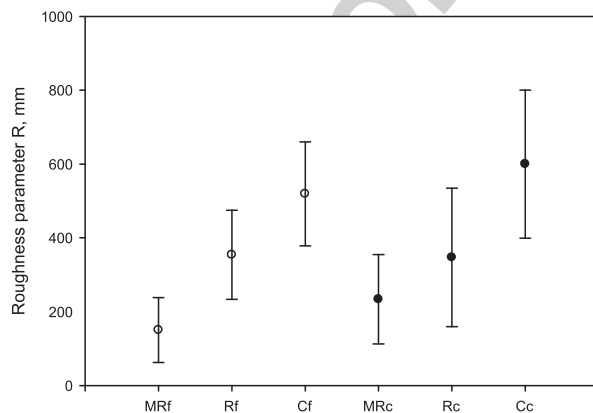


Figure 2. Roughness parameter  $R$  of each treatment (refer to text for explanation). MR, mouldboard plough + roller compacted; C, chisel + harrow, R, rotavator; f and c, parallel and perpendicular to the main slope of the plot, respectively

DS was higher in the tillage carried out perpendicular to the slope, with the exception of MR, in which a higher storage in the treatment parallel to the slope was recorded (MRf in Table II). We do not think that DS in the MRf treatment was really mostly affected by the tillage direction because the scant macroroughness observed in the MR treatments (Figure 2), together with the high slope, would have minimized the contention effect of these macroform. On the other hand, and considering only tillage types, i.e. tillage in both directions, tillage with the rotavator (R) was that which recorded more DS, followed by chisel (C) and then mouldboard plough + roller compacted (MR). As can be seen, the broadly accepted assumption that the greater the roughness the higher the DS (Moore and Larson, 1979; Ullah and Dickinson, 1979a, b; Hansen *et al.*, 1999) was not fulfilled, at least not completely (cf. Figure 2 with Table II).

As mentioned in the preceding texts, up to now, very few works in the field have taken direct measurements of DS by resorting, for this purpose, to impermeabilization techniques on the soil surface or to reproductions of it in impermeable materials (refer to Introduction section). For example, Gayle and Skaggs (1978) managed to measure DS under different conditions, obtaining DS values of between 0.6 and 19 mm, for slopes of 0–0.2%, i.e. maximum DS. They conclude that storage is mainly dependent on the type of soil, tillage and slope, which would explain this wide range of values obtained by those authors. Therefore, their results, although important, are only orientatives and not generalizable.

Additionally, Kamphorst and Duval (2001) measured in the laboratory the maximum DS (i.e. on a levelled surface) of two soil replicates – with a contrasting roughness – made of polyester. Each replicate was created taking a surface artificially prepared by means of the homogeneous dispersion, in an area of 0.5 m<sup>2</sup>, of soil aggregates of under 40 mm, in one case, and under 80 mm



in the other. In this way, roughness values of  $RR=4$  mm and  $RR=15$  mm, respectively, were obtained. The DS values were comprised between 0.4 and 52 mm. It should be pointed out that the measurements of Kamphorst and Duval were taken using edges of different heights, i.e. from 0 mm (with no edge) to 120 mm. Being levelled surfaces, in the experiments with very high edges, the DS values would have been overestimated, as admitted by the authors themselves. In our experiments, we think that the 'edge effect' was minimal, although perhaps a little more important in those treatments with tillage marks perpendicular to the main slope (c). This was not only because the surface sampled was larger and square ( $0.8-1$  m<sup>2</sup>) but also, and mainly, because it was notably inclined ( $\sim 10\%$ , Table II). Also, this important slope meant that our experimental DS values were not maximum ones, as it was the case for those DS values determined by Kamphorst and Duval using a levelled surface, as was indicated.

Similarly, Antoine *et al.* (2012) measured the DS in replicas –  $0.5$  m<sup>2</sup> – of tilled soil ( $RR \sim 10$  mm) with a slope of  $5\%$ , obtaining values slightly over  $1$  mm. These figures are, this time, lower than those obtained in our experiment.

#### Evaluation of the models

The fact that, as mentioned in the preceding texts, no consistent relationship had been observed, between surface roughness and DS foresaw an uncertain performance of the four empirical models studied because they are based precisely on roughness indexes (Table III, F3 Figure 3).

The models whose predictions gave the greatest errors F4 were  $M_T$  and, especially,  $M_{RR}$  (Figures 3 and 4). The latter sometimes predicted even *negative DS* values, and it was the same for the different variants of  $RR$  ( $RR_{Ln}$  and  $RR_{10\%}$ ). The poor performance of the model  $M_{RR}$  would be mostly explained by its being based on a roughness index ( $RR$ ) that only takes into account the distribution of heights (i.e. vertical component of the roughness) and not the spatial distribution of the height measurements (i.e. horizontal component) (Antoine *et al.*, 2012). In fact, and in theory, any two surfaces highly contrasted with respect to their macroforms could have similar  $RR$  values provided that they do not greatly differ in height distribution (Antoine *et al.*, 2012). Also, it should be made clear that the formulation of  $M_{RR}$  (Table III) presupposes that the  $RR$  index was obtained from a height profile corrected both per slope and per the macroforms caused by tillage. However, this second correction was omitted in our case, so that it was to be expected that the constants of the model (Table III) would not completely fit our experimental data.

The negative DS values were precisely given in the treatments carried out perpendicular to the slope, namely where the macroforms along the height profile were maxima (Table V). Mwendera and Feyen (1992) T5 proposed a similar model to that of Onstad (1984) for the estimation of DS but modifying its coefficients. However, in our experiments, the limited number of replications did not permit us to make, at least with any acceptable statistical value, a recalculation of those constants.

Regarding  $M_T$ , let us remember that this model could give a different value depending on the distance separating the measurement points (Kamphorst *et al.*, 2000). In our case, the  $T$  index was determined with a high precision (refer in the preceding texts). Still, the estimation error of this model, as already reported, was also important (Figures 3 and 4).

On the other hand, those models describing the microrelief of the soil in physical terms – and then capable of analyzing the spatial dependence of the roughness – were those with the best performance. That is the case of the models  $M_{num}$ ,  $M_{MUD}$  and  $M_{LS-LD}$  (Figures 3 and 4). However,  $M_{MUD}$  and  $M_{LS-LD}$  tended most of the time to largely underestimate DS, whereas the predicted values of  $M_{num}$  were roughly around the observed ones (Figure 4). Besides,  $M_{num}$  presented the lowest RMSE; notice that even its highest RMSE was smaller than that of the second best model, i.e.  $M_{LS-LD}$  and let alone when compared with the other models (Figure 4). Furthermore, the degree of overlap (DO) between corresponding probability density functions for measured and predicted values – i.e. and index indicative of model predictive ability – (Harmel *et al.*, 2010) is on average three times higher in  $M_{num}$  ( $DO=0.09$ ) than in  $M_{LS-LD}$  ( $DO=0.03$ ). Moreover,  $M_{num}$  would appear to perform better in lesser roughness situations (e.g. refer to MRf and Rf in Figure 3). It can be pointed out that  $M_{num}$  could be underestimating DS in approximately  $25-30\%$  because height profiles shorter than  $2$  m were used (Álvarez-Mozos *et al.*, 2011). However, because runoff would have initiated before all depression were completely filled in (Onstad, 1984; Kirkby, 2002) – because of the Q13 connectivity phenomenon –  $M_{num}$  would be, on the contrary, somewhat overestimating DS.

The relative good performance of  $M_{num}$  is not a surprise because water storage is 'directly' measured through a very intuitive procedure. Nevertheless, this model estimated a (very) different value of DS depending on which of the five replications (height profile) is considered in the calculation leading then to a large variability (Figure 4); the surface roughness resulted more heterogeneous than expected. This anisotropy in the microtopography is also clear if the binary images (water



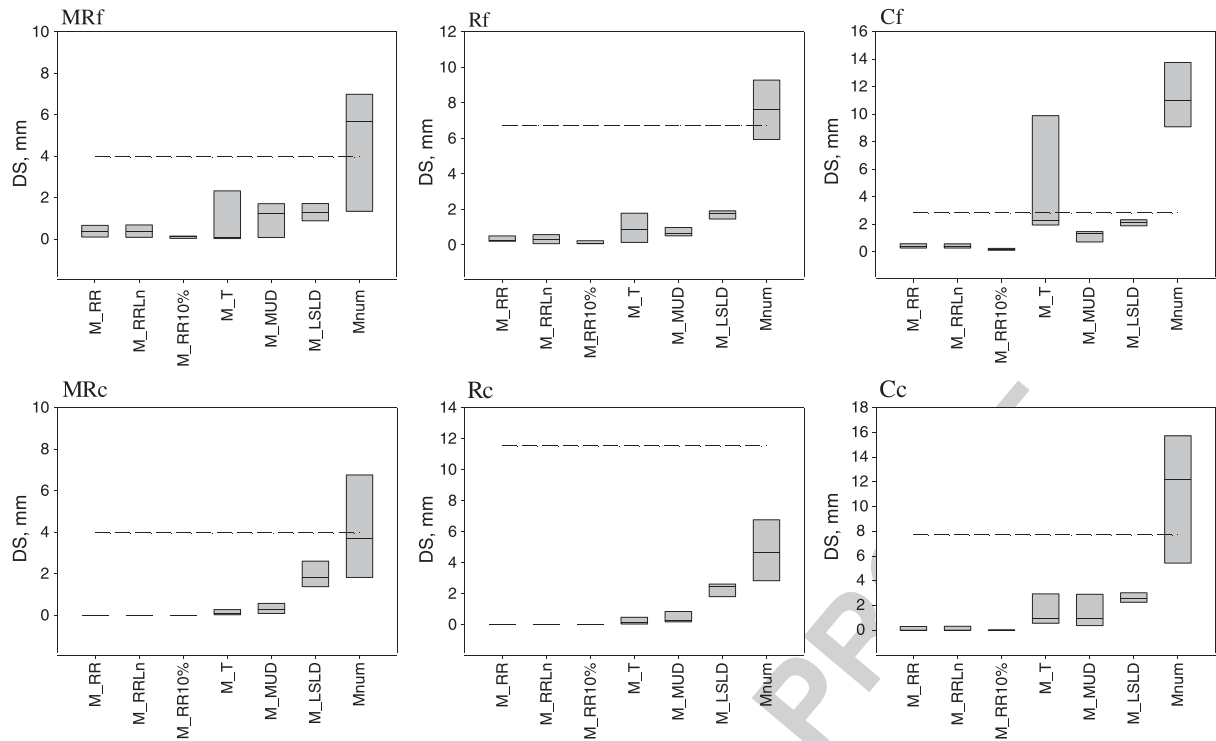


Figure 3. Depressional storage values estimated by the different models in each of the six treatments. RR, random roughness (for more details, refer to text); T, tortuosity; LD, limit elevation difference; LS, limit elevation slope; MUD, mean upslope depression; Num, numerical method; MR, mouldboard plough + roller compacted; C, chisel + harrow; R, rotavator; f and c, parallel and perpendicular to the main slope of the plot, respectively. Each of the discontinuous lines indicates the corresponding average measured value

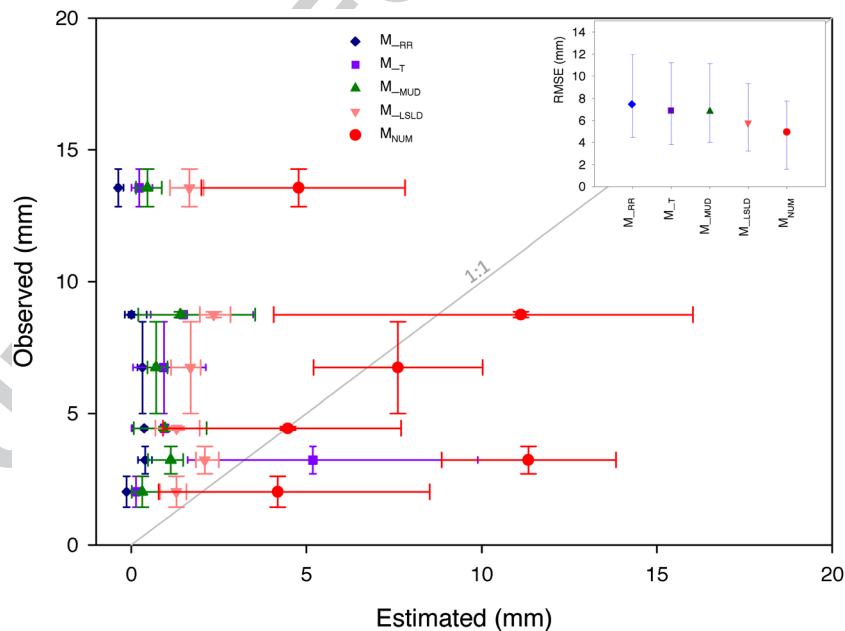


Figure 4. Overall goodness-of-fit evaluation for the different models; root mean square errors were obtained using the computer tool Fiteval (Ritter and Muñoz-Carpena, 2013). M\_RRLn and M\_RR10% were not included because their performance was similar to M\_RR (refer to text for details). Bars are minimal and maximal values

Table V. Average values of depression storage estimated by the models for the different treatments (refer to Table I for descriptions of the treatments)

Model	MRf	Rf	Cf	MRc	Rc	Cc
M <sub>RRsd</sub>	0.37 (0.34)	0.32 (0.19)	0.40 (0.17)	nv	nv	0.10 (0.20)
M <sub>RRLn</sub>	0.39 (0.33)	0.31 (0.26)	0.39 (0.16)	nv	nv	0.10 (0.21)
M <sub>RR10%</sub>	0.10 (0.06)	0.12 (0.13)	0.16 (0.08)	nv	nv	0.004 (0.01)
M <sub>T</sub>	0.95 (1.92)	0.93 (0.86)	5.18 (4.31)	0.13 (0.13)	0.23 (0.24)	1.49 (1.38)
M <sub>MUD</sub>	0.96 (0.89)	0.71 (0.24)	1.13 (0.42)	0.32 (0.29)	0.46 (0.35)	1.40 (1.46)
M <sub>LSLD</sub>	1.29 (0.47)	1.69 (0.32)	2.10 (0.26)	1.95 (0.83)	2.26 (0.42)	2.61 (0.41)
M <sub>num</sub>	4.47 (2.96)	7.61 (1.83)	11.34 (2.35)	4.18 (2.87)	4.77 (2.18)	11.12 (5.49)

Standard deviation in brackets.  
nv, negative values.

storage areas-non-storage areas) of each treatment are analysed (Figure 5). Thus, Figure 5 shows the great variation in the percentage of the surface occupied by water according to whether the total area (0.8–1 m<sup>2</sup>) (dotted line inside each box in the box diagram) or each of the small subareas that come from dividing the total area into 80–100 equal parts were considered. This reflects, in short, the great heterogeneity presented by the surface water storage pattern.

Another limitation that affects the precision of the model M<sub>num</sub> is the impossibility of obtaining, with conventional profilometers, height profiles that are faithful representation of the surface roughness. The fact is that a profilometer takes orthogonal measurements in such a way that the cavities under the large aggregates are not recorded (Kamphorst and Duval, 2001). Therefore, the DS values would be being underestimated, especially in situations with very lumpy soil, i.e. with a greater roughness. This would account for – at least partly – the best prediction made by the

model in less rough treatments (Figure 3) given that, in the smooth microreliefs, the cavities concealed by the aggregates were minimal and the interconnection between the microdepressions in the land was also less complex. The presence of hidden cavities associated with high roughness is suggested when analyzing Figure 6. If the total storage area is multiplied by the average water depth, an estimation of the DS would be obtained (Figure 6, grey bars). It is observed that the DS value, determined in this way, notably differs from the real value (Figure 6, black bars), especially in the treatments with a higher roughness (Rc and Cc). It should be noted that a large part of the error arises when considering a single (average) water depth value instead of considering separated values for the different storage areas. However, this error would be given equally in all the cases, so that the previous comparisons would be valid anyway.

As far as we know, there are very few works in which an exhaustive evaluation of surface water storage has

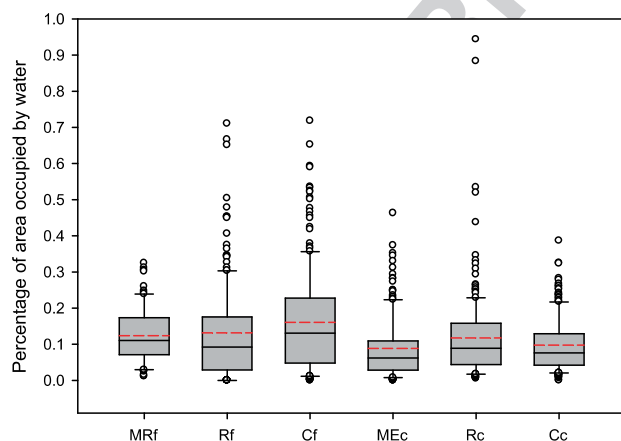


Figure 5. Percentage of the experimental plot surface covered by water in each treatment considering either the total area (0.8–1 m<sup>2</sup>) (discontinuous line within each box plot) or each of the small subareas that result from dividing the total area in 80–100 parts (refer to text for details). MR, mouldboard plough + roller compacted; C, chisel + harrow; R, rotavator; f and c, parallel and perpendicular to the main slope of the plot, respectively

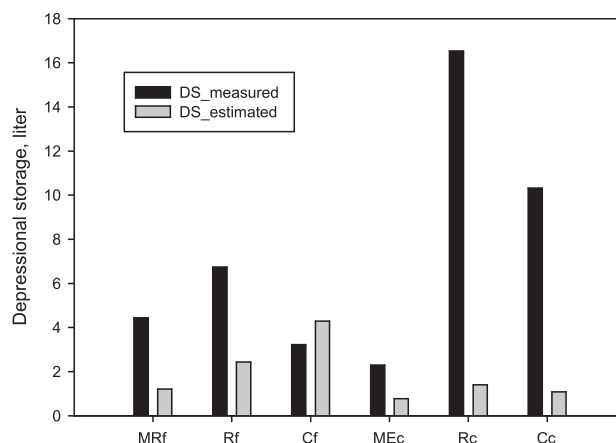


Figure 6. Measured (average value) and estimated DS values in the different treatments. The latter arise from multiplying the total surface area cover by water by the average water depth (refer to text for details). MR, mouldboard plough + roller compacted; C, chisel + harrow; R, rotavator; f and c, parallel and perpendicular to the main slope of the plot, respectively

been made. All of them are characterized by not using, as reference values, direct measurements of DS. Instead, they normally used height measurements from which the soil surface is recreated in two or three dimensions (e.g. Hansen *et al.*, 1999; Vidal Vázquez and Taboada Castro, 1999). Then, with the use of specific algorithms, the water flow over this surface and its storage areas is estimated. However, we have already pointed out the error that would be committed when reproducing the surface's microdepressions by means of measurements taken with profilometers. Furthermore, the intricate interconnection between the innumerable depressions in the terrain results in a very complex flow dynamics (Helming *et al.*, 1998). For example, the soil clods caused by the tillage may present a small area of contact with the underlying soil, thus allowing large unnoticed water flow paths (Antoine *et al.*, 2012) or water accumulation (hidden cavities, as mentioned in the preceding texts). Actually, in our experiments, a complex dynamics in water flow was observed. Therefore, the reliability of the algorithms mentioned is in some way limited (as inferred for instance in McKinney *et al.*, 2012) and the resulting DS reference values as well.

#### Effect of tillage on infiltration rate

Although the infiltration rate associated with a certain DS is a relevant piece of information, the joint measurement of DS and of soil infiltration rate under different tillage conditions is infrequent. As was to be expected, the different tillage types (MR, R and C) altered the soil permeability to water (Table VI) (Falayi and Bouma 1975; Kahlon *et al.*, 2012). In all the cases, an increase in the basic infiltration rate with respect to the original soil values was observed. However, this increase was less than 30% in the treatment C and of over 300% in MR ones. It should be made clear that these values must not be generalized because they could vary, for example, according to soil type and conditions (Govers *et al.*, 2000). Also, it must be remembered that these values correspond to the basic or final infiltration, namely when the soil's moisture content is near to saturation.

Some authors suggest that those types of tillage leaving a greater roughness and, therefore, a higher DS capacity, generate, in turn, an increase in their water infiltration capacity (Kamphorst and Duval, 2000; Zhao *et al.*, 2013). On the contrary, our results, similar to those of Falayi and Bouma (1975), do not show any clear trend between infiltration rate and roughness. In fact, we believe it to be very daring to associate changes in the basic infiltration rate with the surface roughness *per se*, because the soil profile cracking pattern caused by tillage, especially when combining different tillage implements, is not necessarily related directly to the surface roughness perceived by us.

Table VI. Basic infiltration rate for the different treatments

Treatment	DS adjusted (10%) (mm)	Average infiltration rate (mm/h)	% $\Delta I^a$	Evacuation time of DS <sup>b</sup> (min)
MRf	4.44	50.3	318	5.3
MRc	2.30			2.7
Rf	6.74	38.6	221	10.5
Rc	16.54			25.7
Cf	3.23	15.2	27	12.7
Cc	10.32			41

Refer to Table I for descriptions of the treatments.

<sup>a</sup> Percentage difference in infiltration rate compared with infiltration rate before tillage (=12 mm/h, average of five repetitions).

<sup>b</sup> Estimated through the balance DS *versus* infiltration rate.

For instance, in our experiments, the tillage type with the lowest DS (MR) was the one that recorded a higher increase in its infiltration rate (Table VI).

Water storage in soil depressions is able to remain on the surface for a longer or shorter time, precisely according to the infiltration capacity of the soil. For example, our results demonstrate that the Cc treatment permitted the storage of twice the amount of water than MRf (Table II), but in the latter, it infiltrated at a much higher velocity (around four times faster) (Table VI). Thus, one or other tillage application could be desirable depending on the circumstances. For example, if habitually, there were intense rain events of a short duration, that tillage offering a higher DS could be opted for, i.e. Cc. Conversely, if rainfall of a low intensity but over a longer time predominated, the best alternative would be MRf.

## CONCLUSIONS

The DS capacity of the soil both under natural conditions and under those caused by agricultural activity is an important aspect to be taken into account in hydrological studies. However, the great difficulty in measuring the DS directly and precisely has meant that there are very few studies in which this type of determination has been made. Instead, the use of predictive (empirical) models of certain reliability has been resorted to. The models most employed, for their simplicity, are the 2D ones. In this work, exhaustive measurements of DS *in situ* have been carried out in a soil under different type of tillage. These data were then used as reference values for the evaluation of some of the best-known 2D models for DS estimation.

The type of soil tillage and its direction with respect to the general slope notably affects DS capacity of water from rainfall and runoff. In general terms, the highest DS would be found on surfaces with large roughness, especially when the macroforms (triggered by tillage)

cut off the main slope. However, in sloping terrains (e.g. of over 10%) and when the tillage does not generate any very notable macroroughness (for example, that done with a mouldboard plough followed by a roller compacted, MR) the direction of the tillage does not greatly affect that DS.

The empirical DS estimation models had a limited performance. This low accuracy was because of the roughness indexes (explanatory variables) not reflecting adequately the complexity of the surface roughness, especially that related to macroforms. Nonetheless, the 2D numerical method analysed,  $M_{num}$ , was the most effective, even so, with a large variability because of the high heterogeneity of the soil surface roughness and also because very rough soils conceal, under their aggregates, large cavities that cannot be recorded by conventional profilometers. Applying numerical methods in 3D DEMs could improve predictions, as they present a better finished depiction of the land surface. However, the performance of the numerical methods based on 3D DEMs would equally maintain a certain prediction error because the concealed cavities mentioned in the preceding texts would, of course, still be present. Furthermore, as this *underlying* microlief is, to a lesser or greater extent, different from that recreated by means of the 3D DEM, it could, as a result, give rise to a surface water movement also different from that estimated by any of the algorithms existing for that purpose.

Soil tillage affects not only DS but also the water's infiltration rate. It is for that reason that, for a correct hydrological management of the soil, it is not enough to know its instantaneous capacity of surface water storage but also the time of its permanence on that surface.

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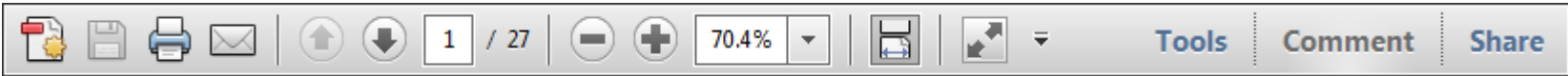
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Q12	AUTHOR: Please check section heading corresponding to section 2.3 if correct.	Correct
Q13	AUTHOR: The citation “Onstand, 1984” (original) has been changed to “Onstad, 1984”. Please check if appropriate.	Appropriate

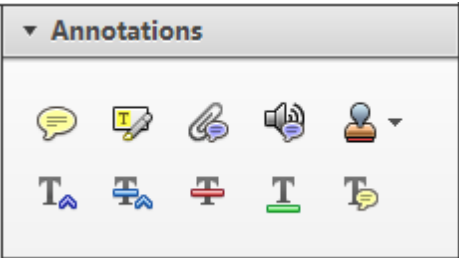
Query No.	Query	Remark
Q14	AUTHOR: The citation “Kamporst and Duval, 2001” (original) has been changed to “Kamphorst and Duval, 2001”. Please check if appropriate.	Appropriate
Q15	AUTHOR: The citation “Vidal Vázquez and Taboada, 1999” (original) has been changed to “Vidal Vázquez and Taboada Castro, 1999”. Please check if appropriate.	Appropriate
Q16	AUTHOR: “Kamphorst and Duval, 2000” is cited in text but not given in the reference list. Please provide details in the list or delete the citation from the text.	In the text it should be 2001 instead of 2000. It is now corrected in text
Q17	AUTHOR: Please provide volume number for references Currence, H. D., Lovely, W. D. 1970.	the reference is now completed
Q18	AUTHOR: Reference “Moore & Larson (1979)” is not cited in the text. Please indicate where it should be cited; or delete from the reference list.	deleted from the reference list
Q19	AUTHOR: Please provide city location of publisher for references Planchon, O. and Darvoux, F. 1999.	Provided: Amsterdam
Q20	AUTHOR: Please provide city location of publisher for references Refsgaard, J. C., B. Storm. 1995.	Provided: Colorado, USA.
Q21	AUTHOR: Please check the issue number if captured correctly.	It was corrected

Required software to e-Annotate PDFs: Adobe Acrobat Professional or Adobe Reader (version 7.0 or above). (Note that this document uses screenshots from Adobe Reader X)  
The latest version of Acrobat Reader can be downloaded for free at: <http://get.adobe.com/uk/reader/>

Once you have Acrobat Reader open on your computer, click on the [Comment](#) tab at the right of the toolbar:



This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the [Annotations](#) section, pictured opposite. We've picked out some of these tools below:



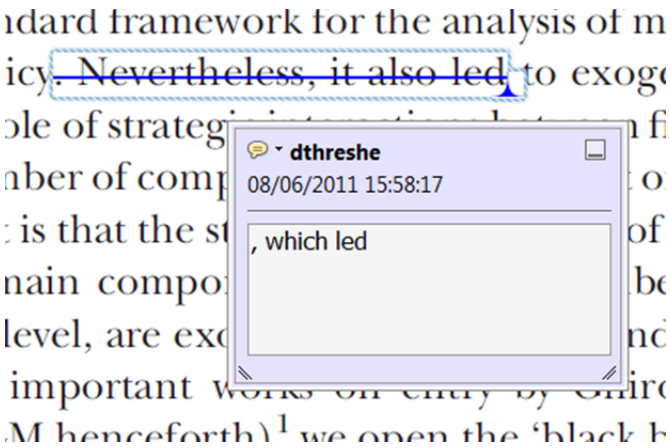
1. [Replace \(Ins\)](#) Tool – for replacing text.



Strikes a line through text and opens up a text box where replacement text can be entered.

How to use it

- Highlight a word or sentence.
- Click on the [Replace \(Ins\)](#) icon in the Annotations section.
- Type the replacement text into the blue box that appears.



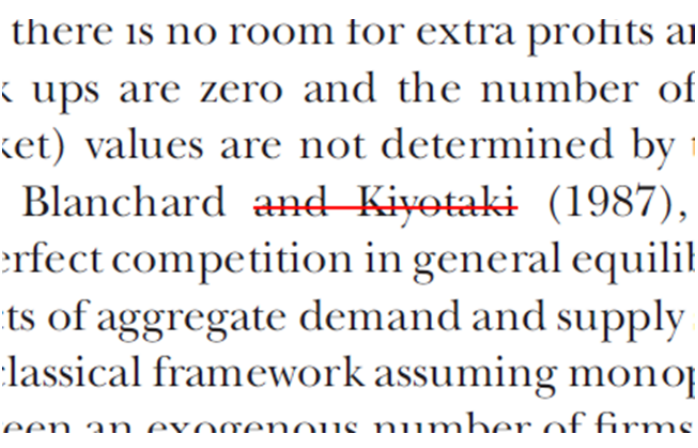
2. [Strikethrough \(Del\)](#) Tool – for deleting text.



Strikes a red line through text that is to be deleted.

How to use it

- Highlight a word or sentence.
- Click on the [Strikethrough \(Del\)](#) icon in the Annotations section.



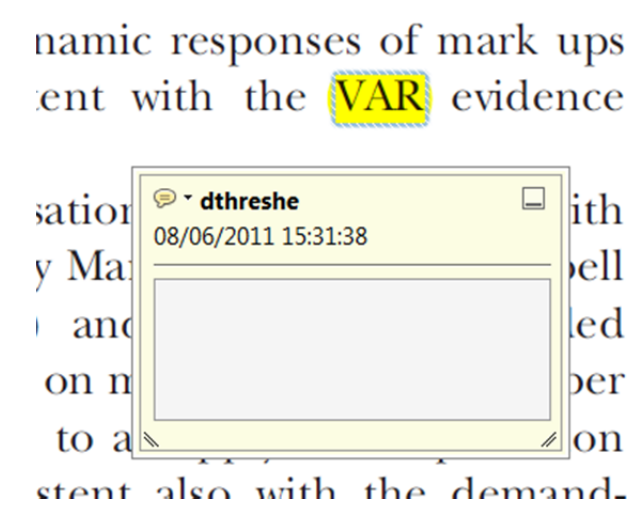
3. [Add note to text](#) Tool – for highlighting a section to be changed to bold or italic.



Highlights text in yellow and opens up a text box where comments can be entered.

How to use it

- Highlight the relevant section of text.
- Click on the [Add note to text](#) icon in the Annotations section.
- Type instruction on what should be changed regarding the text into the yellow box that appears.



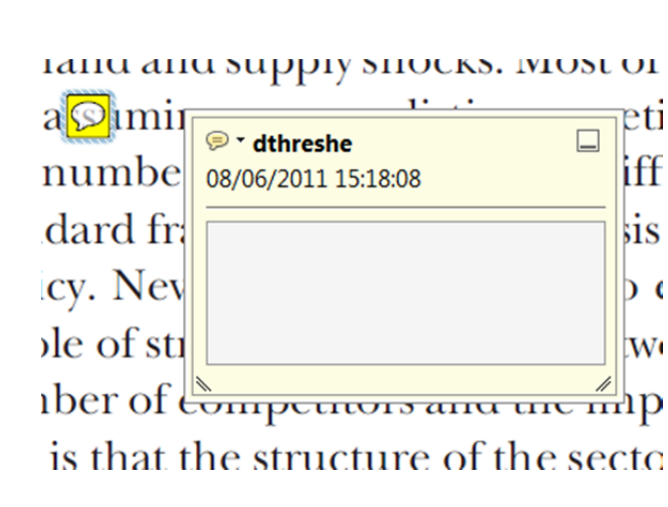
4. [Add sticky note](#) Tool – for making notes at specific points in the text.



Marks a point in the proof where a comment needs to be highlighted.


How to use it

- Click on the [Add sticky note](#) icon in the Annotations section.
- Click at the point in the proof where the comment should be inserted.
- Type the comment into the yellow box that appears.



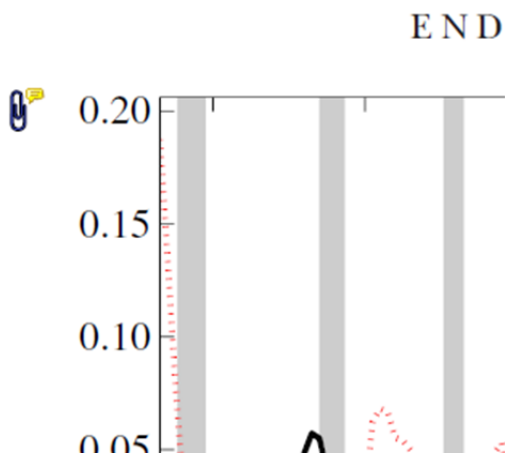


5. **Attach File** Tool – for inserting large amounts of text or replacement figures.


 Inserts an icon linking to the attached file in the appropriate place in the text.

How to use it

- Click on the **Attach File** icon in the Annotations section.
- Click on the proof to where you'd like the attached file to be linked.
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.



6. **Add stamp** Tool – for approving a proof if no corrections are required.

 Inserts a selected stamp onto an appropriate place in the proof.

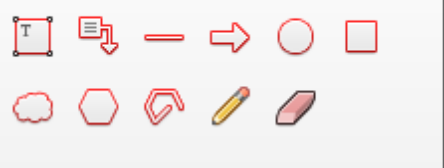
How to use it

- Click on the **Add stamp** icon in the Annotations section.
- Select the stamp you want to use. (The **Approved** stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).

of the business cycle, starting with the  
on perfect competition, constant returns  
production. In this environment goods  
extra profits and the structure of market  
he number of firms in the individual firm  
etermined by the model. The New-Key  
otaki (1987), has introduced product  
general equilibrium models with nominal  
ed and supply shocks. Most of this literat

**APPROVED**

Drawing Markups

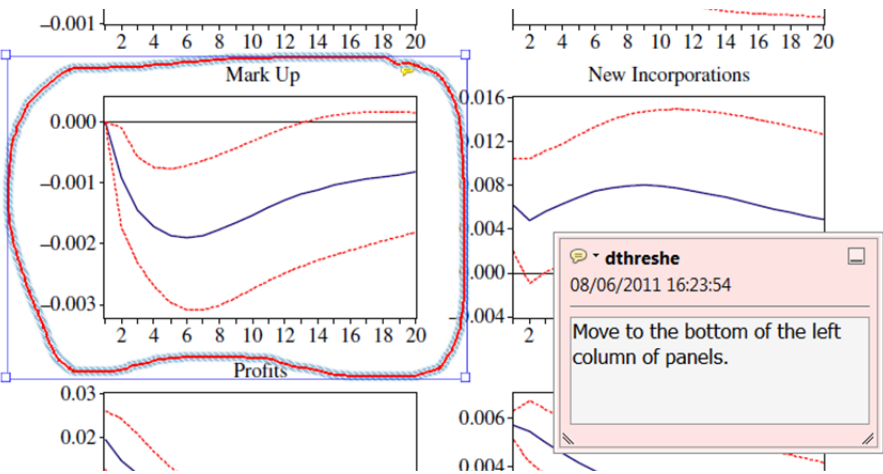


How to use it

- Click on one of the shapes in the **Drawing Markups** section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.

7. **Drawing Markups** Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..



For further information on how to annotate proofs, click on the **Help** menu to reveal a list of further options:

